The η'N interaction and η'-optical potential in nuclear matter

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  - The η' mass and chiral symmetry
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η' mass and chiral symmetry

The possible change of hadron properties in medium : one of the topics of hadron physics

→ Some attempts to investigate the in-medium hadron properties

(Dilepton decay of vector meson, pionic atom,…)

One of the recent interests : *η'* mesic nuclei

K.Itahasihi et al,PTP,128(2012)601.

Key point:

Degeneracy of *η'*(pseudoscalar singlet) and *η*(pseudoscalar octet) mesons in the chiral symmetric phase.

T.D. Cohen, Phys. Rev.D54 (1996) 1867., S.H. Lee, T. Hatsuda, Phys.Rev. D54(1996)54., D. Jido, H. Nagahiro, S. Hirenzaki, Phys.Rev. C85(2012)032201(R).

✓ *η and η' are contained in the same multiplet of $SU(3)_L \times SU(3)_R$.*

Singlet-pseudoscalar meson

$$\eta' \sim \bar{q} i \gamma_5 q \xrightarrow{\text{Axial trans.}} [Q_5^a, \eta'] = -\bar{q} i \frac{\lambda^a}{\sqrt{6}} q$$

$$\xrightarrow{\text{Axial trans.}} [Q_5^a, [Q_5^b, \eta']] = d^{abc} \bar{q} i \gamma_5 \frac{\lambda^c}{\sqrt{6}} q \sim d^{abc} \eta^c$$

Octet-pseudoscalar mesons

(Q_5^a:axial charge (generator of axial trans. of $SU(3)_L \times SU(3)_R$))

⇒ η and η' should degenerate in chiral symmetric phase

Partial restoration of chiral symmetry (PRCS)

Quark condensate @low density

$$\langle \bar{q}q \rangle^* = \left(1 - \frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2}\rho\right) \langle \bar{q}q \rangle + \mathcal{O}(\rho^{n>1})$$

E.G.Durkarev, E.M.Levin, Nucl.Phys. A511, 679(1990).

ρ:nuclear density[fm^{-3}] $\langle \bar{q}q \rangle$:quark condensate in free space

$\sigma_{\pi N} = 2m_q \langle N|\bar{q}q|N \rangle$ $\langle \bar{q}q \rangle^*$:quark condensate in nuclear matter

The possibility of the reduction of 〈$q^{bar}q$〉 in the nuclear matter

The reduction of 〈$q^{bar}q$〉 can affect the hadron properties.

Ex.) Gell-Mann-Oakes-Renner relation

$f_\pi^2 m_\pi^2 = -m_q \langle \bar{q}q \rangle$ ⇨ Change of the hadron properties (decay const. or mass)

※Experimental investigation of PRCS @normal nuclear density with nucleus target

⇨ **The 35% reduction of 〈$q^{bar}q$〉@normal nuclear density is suggested.**

- π atom:K.Suzuki, et al., PRL92,72302(2004).
- π-nucleus elastic scattering:E.Friedman, et al., PRL93,122302(2004).

The degeneracy of *η* and *η'* in chiral SU(3) symmetric phase

←
- Partial restoration of chiral symmetry
- small change of *η* mass in nuclear medium

<u>The possibility of the η' mass reduction in the nuclear matter</u>

<u>through the partial restoration of chiral symmetry</u>

Related works:

☐ The *η'* mass in finite T, μ with chiral effective models

V.Bernard et al., PRD38(1988)1551.,T.Hatsuda, T.Kunihiro, Phys. Rep247(1994)221., P.Costa,et al.,Phys.Lett.B569(2003)171.,J.T.Renaghan, et al. PRD62,085008(2000). H.Nagahiro,et al.PRC74(2006)045203.,…

☐ The relation between *η'* mass and the nuclear density

$$\Delta m_{\eta'} = \frac{2}{3}\frac{m_{\eta'}^2 - m_\eta^2}{2m_{\eta'}}\frac{\sigma_{\pi N}}{m_\pi^2 f_\pi^2}\rho$$

→80-100MeV mass reduction of *η'* @normal nuclear density

S.S,D.Jido,PRC88,064906.

η' mass reduction and η'-optical potential in nuclear matter

・Mass reduction and optical potential

Klein-Gordon eq. : $$\left(-\nabla^2 + m_{\eta'}^2 + \Sigma_{\eta'}(\rho)\right)\Phi = E^2\Phi$$

η' mass in free space

In-medium η' mass

The in-medium η' self energy

The in-medium self energy can be seen as the optical potential in nuclear medium.

Large mass reduction of η'
〜strong attraction of η' to nuclei
Local density approximation

The possibility of the η'-mesic nuclei

→ The effort to observe the η'-mesic nuclei

Itahasihi et al,PTP,128(2012)601.

※The width of the bound state is important for the observation

Less information of imaginary part of the η' optical potential

To understand the η'-optical potential with more microscopic way,…

→ The *η'N interaction* is elementary process.

The purpose

- Evaluation of the η'N interaction with chiral effective model
  - ✓ η'N elastic and η'N-ηN channel
  - ✓ not known well
  - ✓ important quantities for the in-medium η' property
- The η'-optical potential in nuclear matter with the interaction

The important effects:

- Symmetries of QCD ($SU(3)_L \times SU(3)_R$, $U(1)_A$ anomaly,…)
- Introduction of symmetric nuclear matter with a consistent way with the partial restoration of chiral symmetry
- Nucleon degree of freedom

⇨ **Analysis with the linear sigma model**

Lagrangian of linear sigma model

J.Schechter,Y.Ueda,Phys.Rev.D3,168(1971).
J.T.Renaghan, et al. PRD62,085008(2000).

$$\mathcal{L} = \frac{1}{2}\mathrm{tr}(\partial_\mu M \partial^\mu M^\dagger) - \frac{\mu^2}{2}\mathrm{tr}(MM^\dagger) - \frac{\lambda}{4}\mathrm{tr}\left[(MM^\dagger)^2\right] - \frac{\lambda'}{4}\left[\mathrm{tr}(MM^\dagger)\right]^2 + A\mathrm{tr}\chi M^\dagger + \sqrt{3}B\det M + \mathrm{h.c.}$$

The effect from the current quark mass

$U_A(1)$ anomaly effect

$$+\bar{N}i\partial\!\!\!/ N - g\bar{N}\left(\frac{1}{\sqrt{3}}\sigma_0 + \frac{1}{\sqrt{6}}\sigma_8 + i\gamma_5\frac{\vec{\tau}\cdot\vec{\pi}}{\sqrt{2}} + i\gamma_5\frac{1}{\sqrt{3}}\eta_0 + i\gamma_5\frac{1}{\sqrt{6}}\eta_8\right)N$$

Contribution from nucleon

$$M = \sum_{a=0}^{8}\frac{\sigma_a\lambda_a}{\sqrt{2}} + i\sum_{a=0}^{8}\frac{\pi_a\lambda_a}{\sqrt{2}} \quad N = \begin{pmatrix} p \\ n \end{pmatrix} \quad \chi = \sqrt{3}\begin{pmatrix} m_u & & \\ & m_d & \\ & & m_s \end{pmatrix} = \begin{pmatrix} m_q & & \\ & m_q & \\ & & m_s \end{pmatrix}$$

(λ_a:Gell-Mann matrix, τ_i:Pauli matrix)

※1.) 6 free parameters are fixed to reproduce in-vacuum meson properties and 35% reduction of quark condensate @normal nuclear density.

π atom:K.Suzuki, et al., PRL92,72302(2004).
π-nucleus elastic scattering:E.Friedman, et al., PRL93,122302(2004).

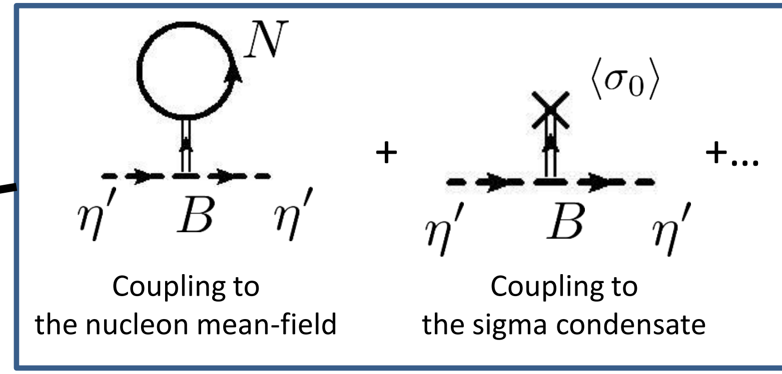
※2.) $\langle\sigma_0\rangle\neq 0$ when chiral symmetry is broken (with spontaneous and explicit breaking).

※3.) $\langle\sigma_8\rangle\neq 0$ when flavor symmetry is broken ($m_q\neq m_s$).

In-medium η' mass

- <u>η' mass in chiral limit</u>

$$m_{\eta'}^{*2} = 6B\langle\sigma_0\rangle^*$$



The contribution
from the $U_A(1)$ anomaly

The contribution
from the chiral symmetry breaking

(Non-zero values in the chiral limit if chiral symmetry is broken.)

The necessity of both the $U_A(1)$ anomaly and chiral symmetry breaking
for the generation of the η' mass

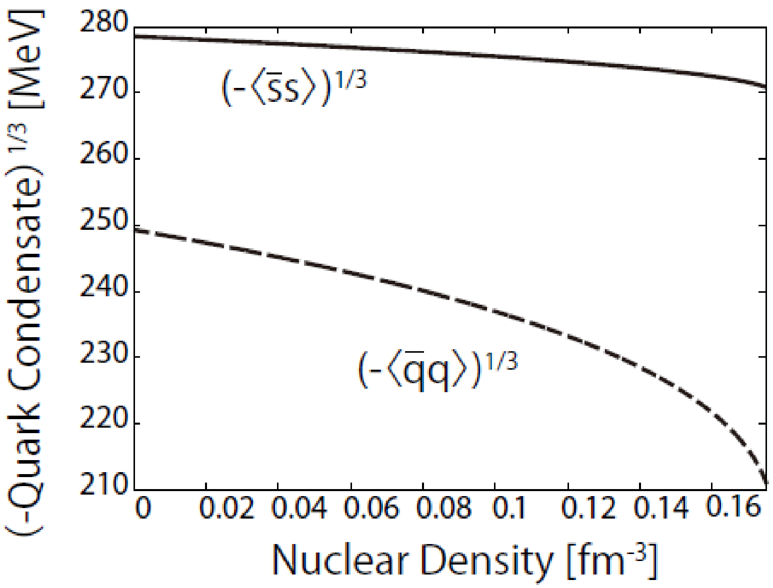
※The π mass vanishes in chiral limit

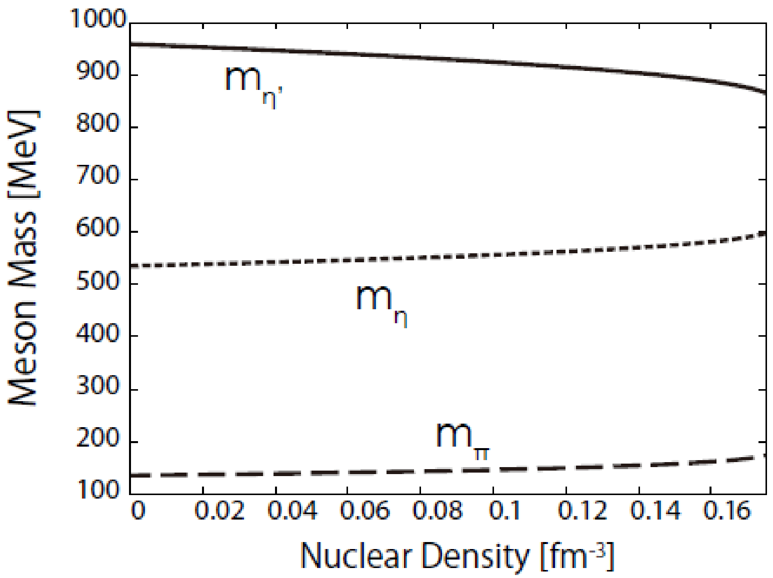
$$m_{\pi}^{*2} = \frac{6Am_q}{\langle\sigma_0\rangle^* + \frac{\langle\sigma_8\rangle^*}{\sqrt{2}}} \rightarrow 0 \quad (m_q \rightarrow 0)$$

In-medium η' mass with the linear sigma model

S.S,D.Jido,PRC88,064906.

- Nuclear density is introduced with Mean-Field approximation





The 35% reduction of $\langle q^{bar}q\rangle$ @$\rho=\rho_0$ is input.

π atom:K.Suzuki, et al., PRL92,72302(2004).
π-nucleus elastic scattering:E.Friedman, et al., PRL93,122302(2004).

About 80MeV reduction of η' mass @ $\rho=\rho_0$
About 50MeV enhancement of η mass @ $\rho=\rho_0$

⇨ Mass difference between η and η' reduces about 130MeV.

(The partial restoration of chiral symmetry leads to the degeneracy of η and η')

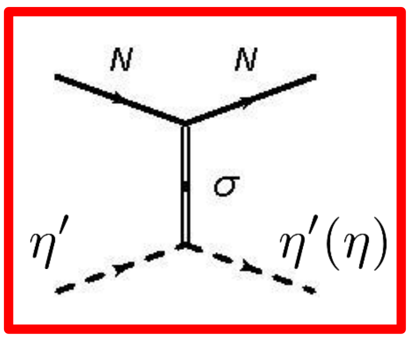
The η'N interaction
with the linear sigma model

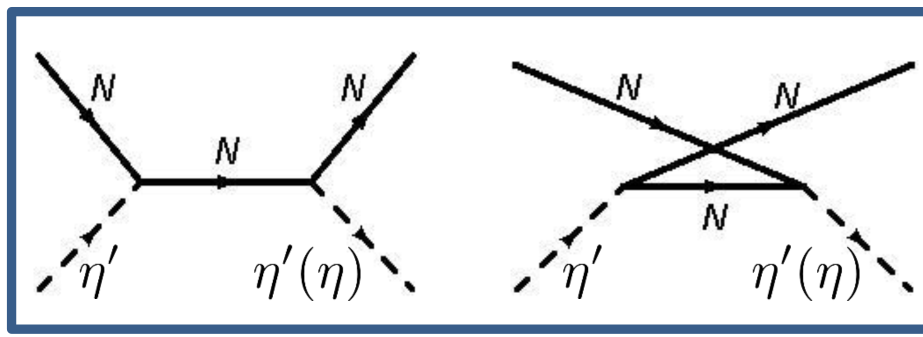
η'N interaction

- η'N interaction (η'N-η'N, η'N-ηN)

  in the linear sigma model @tree level

Tree level diagrams





Scalar meson exchange

Born term (containing nucleon intermediate state)

The η'N interaction in low energy and chiral limit

Model dependence is small (low energy theorem)

η'N scattering amplitude

The η'N interaction in low energy and chiral limit

$$V_{\eta_0 N} = -\frac{g^2}{\sqrt{3}m_N}\frac{m_{\eta_0}^2}{m_{\sigma_0}^2} \quad V_{\eta_0 N \to \eta_8 N} = \frac{\sqrt{2}g^2}{3m_N}\frac{m_{\eta_0}^2}{m_{\eta_0}^2 + m_{\sigma_8}^2}$$

- The contribution from the scalar meson exchange term
- momentum independent interaction
- $U_A(1)$ anomaly is essential for $V_{\eta 0N}$, $V_{\eta 0N \to \eta 8N}$.

✓different from the ordinary NG bosons
(Scalar meson exchange terms are cancelled out
and energy-dependent Weinberg-Tomozawa term remains .)

The η'-optical potential in nuclear matter

The η'-optical potential in nuclear matter

Evaluating the self energy of η' in nuclear matter

$$V_{\eta'}(\rho) = \frac{1}{2m_{\eta'}} \Sigma_{\eta'}(\rho)$$

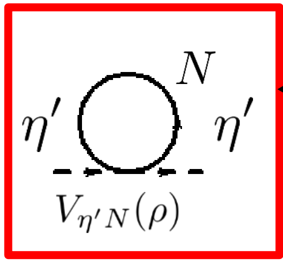
The η' optical potential in nuclear matter

The in-medium η' self energy

Diagrams

η'N Vertices : from LSM analysis

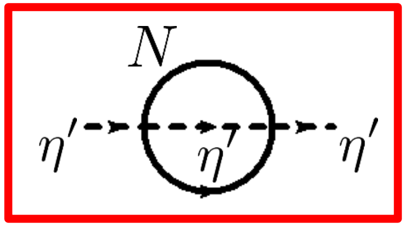
- ***Real Part:***

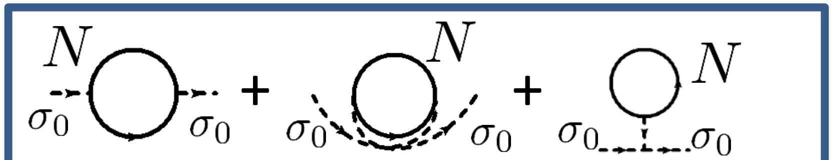


$$V_{\eta_0 N} = -\frac{6gB}{\sqrt{3}m_{\sigma_0}^2}$$

(from LSM analysis)

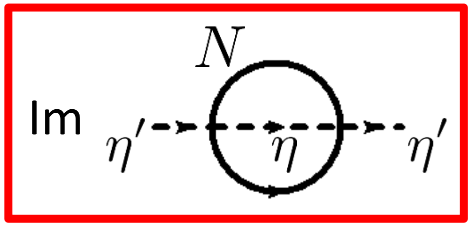
Softening of σ is also one of interesting feature in chiral restoration





Effect of the σ mass modification in nuclear matter

- ***Imaginary Part:***



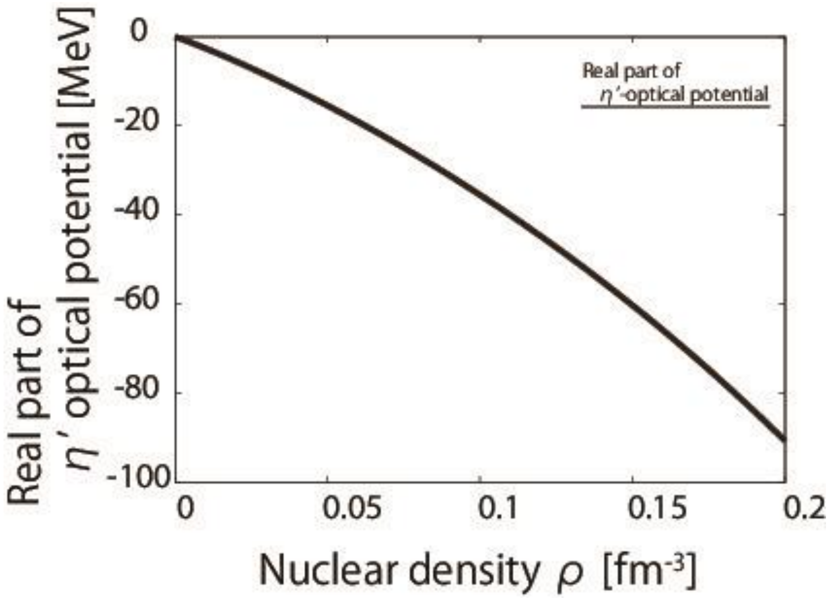
The nuclear matter effect comes from the nucleon loop.

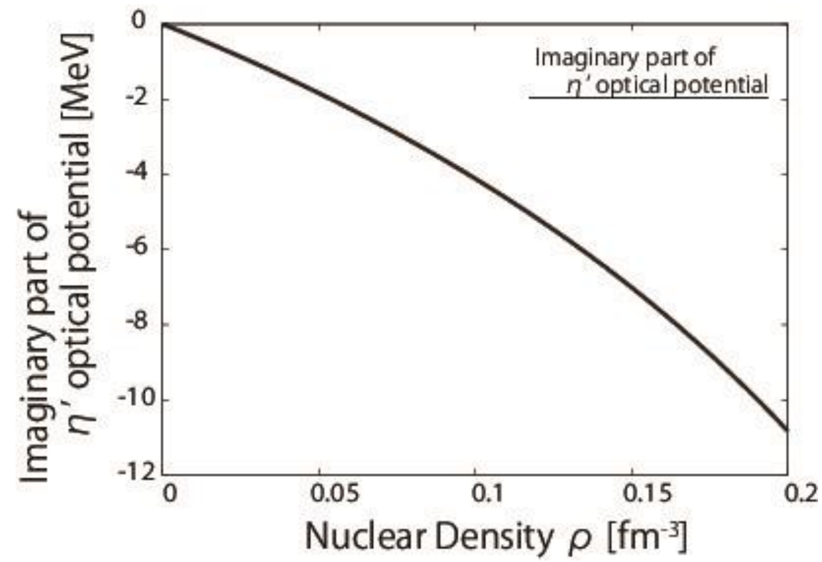
$$(\not{p} + m)\left\{\frac{i}{p^2 - m^2 + i\epsilon} - 2\pi\theta(p_0)\delta(p^2 - m^2)\theta(k_f - |\vec{p}|)\right\}$$

Free propagation

Pauli Blocking

The η'-optical potential in nuclear matter





$V(\rho=\rho_0)=-70-8.0i$ [MeV]

($\rho_0=0.17\text{fm}^{-3}$)

- Strongly attractive potential
- Small imaginary part compared to the real part → small width

→ **Desirable for the observation of the η'-mesic nuclei**

Summary

- The η'N interactions with LSM
  - $U_A(1)$ anomaly is essential for the interaction
- The η'-optical potential in nuclear matter
  - strong attraction and small absorption

  : -70-8i [MeV] @$\rho=\rho_0$

Future Prospects:

・The calculation of binding energy of η' and nucleus with the optical potential.

・The application for the η'N system